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DEVELOPMENT OF AN X-WINDOWS TOOL TO COMPUTE GAUSSIAN BEAM SYNTHETIC SEISMOGRAMS

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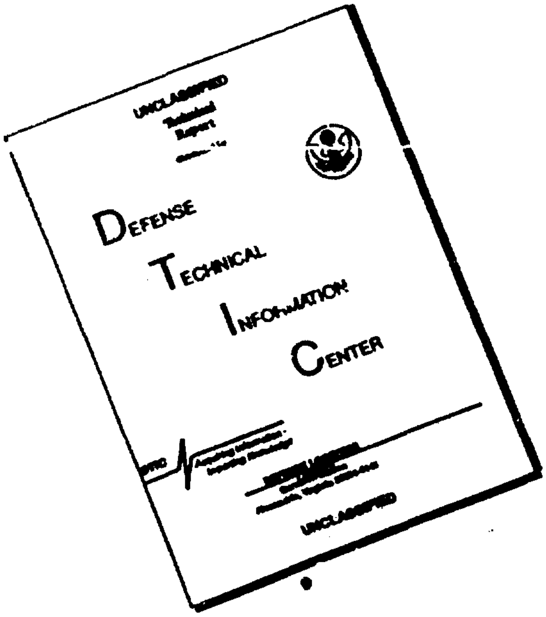

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The principal goal of this project was to create an X-Windows-based graphics tool to compute rapidly and efficiently, synthetic seismograms for laterally heterogeneous, two-dimensional (2-D), isotropic velocity models using the Gaussian beam method and to integrate that tool into the software environment at the Center for Seismic Studies (CSS). Existing Gaussian beam software is written in Fortran code and is often very cumbersome to use. By constructing an X-Windows Graphical User Interface (GUI) to augment the original code, much of the tedium of introducing lateral heterogeneity into 2-D velocity models is eliminated. The tool can be used to aid the interpretation of waveforms or to study how lateral structure and the source's location within that structure impact arrival times and waveform shape. This report contains an outline of the system's functionality and a description of several accuracy tests which were performed. A User's Manual is provided separately as report TGAL-93-02 "*User's Guide to Xgbm: An X-Windows System to Compute Gaussian Beam Synthetic Seismograms*." This latter document and the code itself are available by anonymous ftp from CSS.

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1. OBJECTIVES

The principal goal of this project was to create an X-Windows-based graphics tool to compute rapidly and efficiently, synthetic seismograms for laterally heterogeneous, two-dimensional (2-D), isotropic velocity models using the Gaussian beam method and to integrate that tool into the software environment at the Center for Seismic Studies (CSS). Existing Gaussian beam software is written in Fortran code and is often very cumbersome to use. By constructing an X-Windows Graphical User Interface (GUI) to augment the original code, much of the tedium of introducing lateral heterogeneity into 2-D velocity models is eliminated. The tool can be used to aid the interpretation of waveforms or to study how lateral structure and the source's location within that structure impact arrival times and waveform shape.

This report consists of a brief introduction, an outline of the system's functionality and a description of several accuracy tests which were performed. A User's Manual is provided separately as report TGAL-93-02 "*User's Guide to Xgbm: An X-Windows System to Compute Gaussian Beam Synthetic Seismograms*." This latter document as well as the code itself is available by anonymous ftp from CSS. They may be found in the directory ~ftp/pub/davis as compressed tar files.

2. INTRODUCTION

Code written under this contract is based upon Fortran programs written by Michael Weber of the Seismic Central Observatory, Erlangen, Germany, and described by him in *Weber* (1988a). In that paper the principles of Gaussian beam computations are reviewed and its particular implementation, also valid in this context, is described. Weber's programs have been used in a number of applications (*Weber*, 1988b; *Davis et al.*, 1989; *Weber*, 1990; *Weber and Davis*, 1990) to study the effects of 2-D heterogeneous media on seismic waveforms.

The original Fortran was entirely translated into C to better integrate it with the new graphics components. The final release was compiled on both a Sun SPARC 1+ running under OS 4.1.3 and a Silicon Graphics Crimson Elan running under IRIX 4.0.5. On the SPARC, X11 Release 5 was employed to create the graphics components; on the Crimson, X11 Release 4..

The modules of the system are capable of interaction with other CSS software, particularly the *geotool* display program and the Geographic Information System (*Fielding et al.*, 1992). Using *geotool*, the user can select a specific segment of observed data for modeling and superimpose the computed synthetics on the same display in a matter of moments. Using the Geographic Information System (GIS), the user can construct complicated cross-sections including surface topography and crust of variable thickness, based upon information contained in the GIS. Examples are shown below.

The system has been installed on the research LAN at CSS. A beta release of the software was made available to DARPA contractors, and groups at the Ruhr University, Southern Methodist University, the Oklahoma Geological Survey, and the GFZ Potsdam report they have used the programs at their respective institutions. DARPA contractors will be notified of the availability of the final release.

3. FUNCTIONAL OUTLINE

The functional flow for computing Gaussian beam seismograms and/or calculating traveltimes through heterogeneous media is shown in Figure 1. The first step is to create an input model from scratch or to access a fully two-dimensional model which has been created previously. The former is generally done by beginning with a one-dimensional (1-D) model and extending it into a second dimension. Once in this extended form the user may impose large-scale heterogeneity, such as a subduction zone in the case of a global model, or a localized heterogeneity, such as a sedimentary basin with low-velocity lens in the case of a regional model. Additional heterogeneity may be created by manipulating the model elements manually with a mouse. Whether created *ab initio* or read in and modified, the model may be stored for future use.

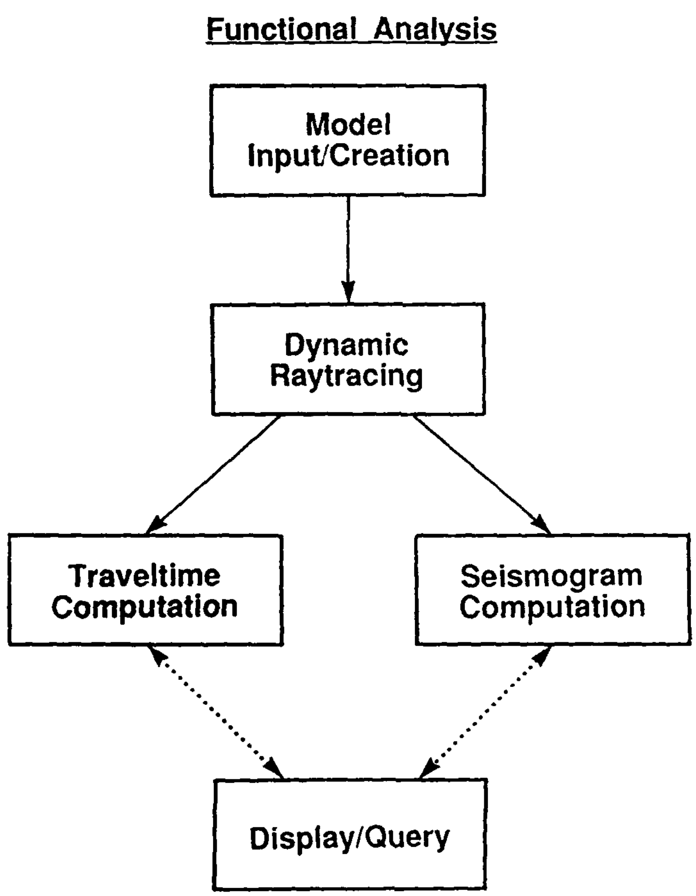

Figure 1. System flow diagram.

The velocity model is specified as a series of knotpoints and triangles. Each knotpoint fixes v_p, v_s, and ρ at a point in space. Because the velocity gradient is assumed to be linear between each knotpoint, the velocity is effectively specified fully in two dimensions. (One exception is at discontinuities: there two knotpoints are spatially co-located and specify the velocity and density on each side of the discontinuity.) Knotpoints are grouped into triplets to form triangles. A value for Q_α and Q_β, the *P*- and *S*-wave attenuation, is assigned to the space enclosed by each triangle. The system tracks which triangles share knotpoints and are therefore "neighbors."

Under these linear gradient conditions, there is an analytical solution for the raypath across a triangle. Once the position of the source has been specified and the phases to be traced have been chosen, raytracing through the model is accomplished by tracing stepwise analytically through each component triangle along the raypath. Anelasticity is accounted for by computing a t^* operator using Q_α and Q_β from the triangles. Results from this step are also stored for later computation of seismograms.

At this point, the essentials for traveltime calculation or seismogram computation are complete. In the Gaussian beam method, it is not necessary to compute rays which travel directly from source to receiver. Rather, it is sufficient to compute a number of rays which originate at the source and terminate within several wavelengths of the receiver. It is possible to generate a traveltime curve without specifying the receiver position. However, to obtain a seismogram, one must first specify precisely the position of the receiver relative to the source. The seismogram consists of a weighted sum of rays which terminate within the required wavelength limit of the receiver. Traveltimes for distances not corresponding to a ray endpoint are found by using slowness to extrapolate the traveltime of the nearest terminating ray.

A Gaussian beam's wavelength and curvature can be calculated in several ways which Weber reviews in his paper. Depending upon what type of wave one is trying to synthesize and certain properties of the model, one way may be superior to another. The user may choose from a wide selection of options and compare outcomes to seek an optimal solution. The computed synthetic seismograms are written out in CSS 3.0 schema format. In keeping with the modular design of the package, the system provides no capability for displaying the synthetic seismograms. Programs to display CSS format data are available through CSS.

4. SYSTEM ARCHITECTURE

How the functional capabilities are realized is outlined in Figure 2. In this diagram, rectangles represent programs with an X-windows graphical component, ellipses enclose the names of background processes, and arrows represent information passed between processes. If the arrow is solid, this information is transmitted via interprocess communication (IPC) routines, either the ISIS programs used for some time at CSS, or the new *ipcc* routines. The dashed arrow connecting *GIS* and *Xgbm* represents an intermediate process that performs a combination of SQL queries and IPC message generation. The modules developed during this project are *Xgbm* and *GBseis*.

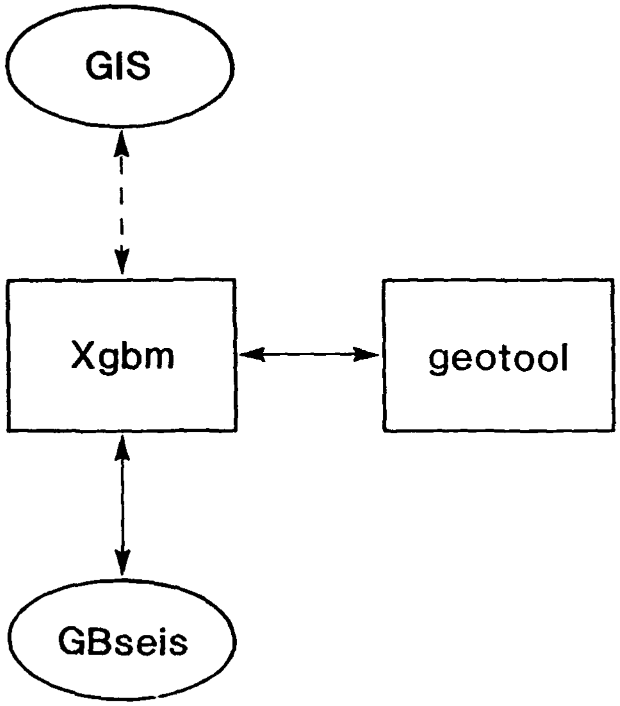

Figure 2. Module connectivity.

Xgbm handles all velocity model manipulation and acts as the hub of all IPC communication. Source-receiver geometry may be set either by *Xgbm* graphics (non-IPC) or by IPC messages received by *Xgbm*. In limited cases, phases to be traced are selected via IPC messages as well, but in general, the user should select the phases using *Xgbm* lists. All raytracing is performed by *Xgbm*. Once the raytracing results are written to an output file, seismograms and/or traveltimes may be obtained in either mode from *GBseis*. For convenience, *Xgbm* may be used to specify the source-time function and source type, but this is not necessary.

GBseis was designed as a separate process so that it could run continuously in background and be thus available to respond to traveltime queries from IMS modules. By segregating the graphics components in the *Xgbm* module, the size of *GBseis* could be reduced considerably. As an increasing number of 2-D velocity models are created, *GBseis* will be able to respond more flexibly to IMS demands.

5. INTERACTION WITH OTHER PROGRAMS

Using IPC message formats detailed in an Appendix to the User's Manual, other DARPA software will be able to take advantage of the *Xgbm* system output. Examples of two systems for which interaction was explicitly designed are listed below.

geotool. *Xgbm* and the interactive display program *geotool* are capable of ex ' ‌ang-ing key information, as illustrated in Figure 3. In this example, seismograms reco\ \ J at the GRF array in Erlangen, Germany, of a deep Kurile Islands earthquake have been examined using *geotool.* In order to better understand what phase follows the direct *P* phase, the user designated a time segment, indicated by the two vertical lines, and selected traces, in this instance all vertical sensors, to be modeled in the synthetic seismogram computation.

Information about which traces are selected, their temporal parameters, phases already identified in the selected traces, and any information *geotool* possesses of the origin, was then solicited with an IPC query by *Xgbm. Xgbm* positioned source and receivers in the velocity model, and the user then manipulated phase choices and ray parameters until satisfied that the seismograms were modeled adequately. In response to a second IPC message from *Xgbm, geotool* then automatically displayed the completed synthetic seismograms. These are shown here superimposed on the observed data. When viewed on a color terminal, it is much easier than here to distinguish observed from synthetic.

Of the two phases clearly visible in the data, one is elementary to identify (direct *P*) but the other is not. When used as an analysis tool, the user could vary the source position, the phases to be included in the computation, and the source type/wavelet shape in order to identify all arrivals in the traces and to refine the location of the event. For research purposes, all the above may be changed, and even the velocity model may be perturbed in order to satisfy the data. Such was the case in this figure -- the secondary phase results from reflections off a structure not far from the core-mantle boundary.

GIS. One of the newest and most useful features of *Xgbm* is the program's ability to make use of surface topography and depth-to-moho information contained in geographic databases and available through raster server programs such as described by *Fielding et al.* (1992). Figure 4 illustrates *Xgbm*'s rendering of the information that *Fielding et al.* (1992) used to create their Figure 5. Shown are cross-sections extending 4000 km north and south from GERESS. Surface topography, sediment thickness, and depth-to-moho are all included.

To produce this figure required entering the latitude and longitude of the cross-section endpoints into an *Xgbm* text widget. *Xgbm* took these coordinates and spawned a process which contacted the raster server at Cornell and created an ASCII file containing the topographic information as a function of distance along the cross-section. *Xgbm* then read the file and modified the simple two-layer crust over a half-space which served as the model basis. The User's Manual provides enough format information for the user to create other, similar ASCII files and have *Xgbm* modify any model discontinuity on the basis of that information.

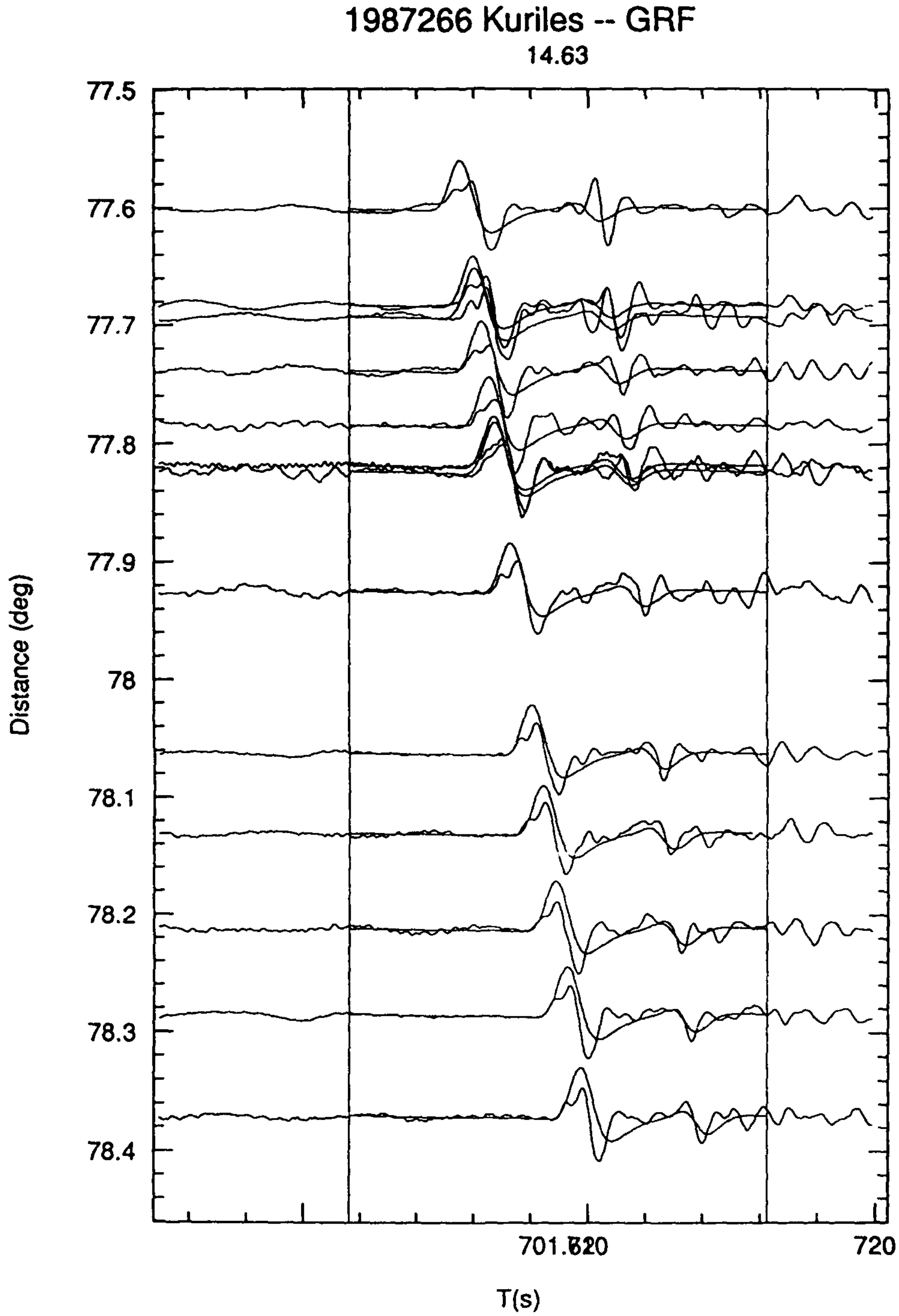

Figure 3. *geotool* display of observed and synthetic seismograms for a deep (h=113 km) Kurile Is. earthquake recorded at the GRF array. Selected parameters for the time segment indicated by the two vertical lines were extracted and passed to *Xgbm* by IPC message. Synthetic seismograms were then computed and automatically superimposed by *geotool*.

(a)

(b)

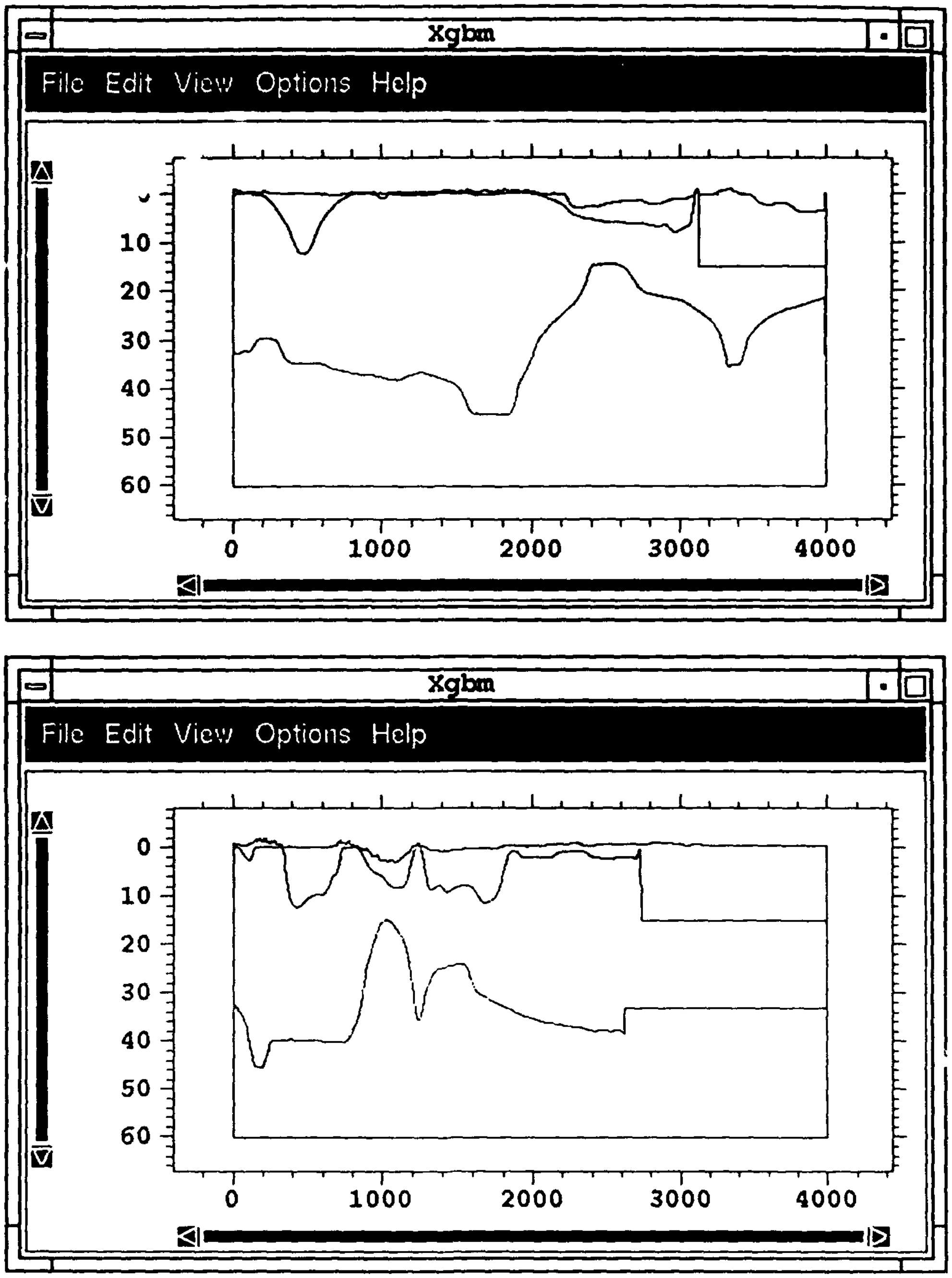

Figure 4. *Xgbm* rendition of surface topography, sediment thickness, and moho depth from information extracted from the Geographic Information System at Cornell for lines running due north (a) and south (b) from the GERESS array. This should be compared to Figure 5 of *Fielding et al.* (1992). The horizontal lines on the right are created when there is no information about the sediments or moho available and the program defaults to using the base model, in this case a crust with layers at 15 km and 33 km depth.

6. ACCURACY TESTS

Tests were conducted on two aspects of the system's performance: the correct computation of traveltimes and the synthesis of waveforms.

Traveltimes. Traveltimes were checked by comparing *Xgbm* computations with values found in three published tables (*Jeffreys and Bullen*, 1940; *Herrin et. al.*, 1968; and *Kennett*, 1991). Table 1 summarizes the comparison.

Traveltime Accuracy

src depth (km):	0	50	100	200	300	400	500	600
iaspei91 (P)	0.06	0.06	0.04	0.07	0.05	0.06	0.04	0.05
iaspei91 (S)	0.08	0.08	0.07	0.06	0.07	0.05	0.04	0.08
herrin.orig (P)	0.05	0.06	0.06	0.06	0.05	0.04	0.04	0.03
herrin.abr (P)	0.05	0.06	0.05	0.06	0.05	0.03	0.05	0.04
jb (P)	1.09	0.90	0.76	0.64	0.61	0.33	0.34	0.39
jb (S)	1.69	1.62	1.27	1.14	1.10	1.17	1.38	1.24

Traveltimes of direct *P* and *S* were computed for a broad sample of source-receiver distances and source depths. Entries represent the standard deviation of residuals in seconds after the published table value was subtracted. Each column corresponds to a distinct source depth. When a table included *S* phases (jb and iaspei91), both *P* and *S* are shown in separate rows. The terms herrin.orig and herrin.abr refer to the complete and smoothed Herrin models, respectively.

The principal source of error is believed to be the method of depth interpolation. Generally speaking, almost every published earth model employs a different interpolation scheme to determine velocity between the depths at which velocity is fixed. *Xgbm* always interpolates linearly with depth, so if the published model employed a different scheme, there will certainly be some error introduced.

By far the largest errors are for the JB model. The original JB tables are just that and do not include a velocity distribution, unlike the other two models cited here. This error is almost certainly caused by an inadequate representation of the table traveltimes by the velocity model given.

Waveforms. The basis for testing the accuracy of the waveforms was to compute seismograms for identical models using the new code and Weber's original Fortran code and to compare the results. Weber's programs have been checked thoroughly against reflectivity and finite difference calculations. Three tests taken from *Weber* (1988a; referred to hereafter as W88a) are illustrated here.

The first was to create several converted phases for a shallow point source in a simple two-layer crust. This is shown in Figure 5 and should be compared to W88a-Figure 5b. Both are plotted with a reducing velocity of 6.3 km/s. The waveform amplitudes and shape have been faithfully reproduced.

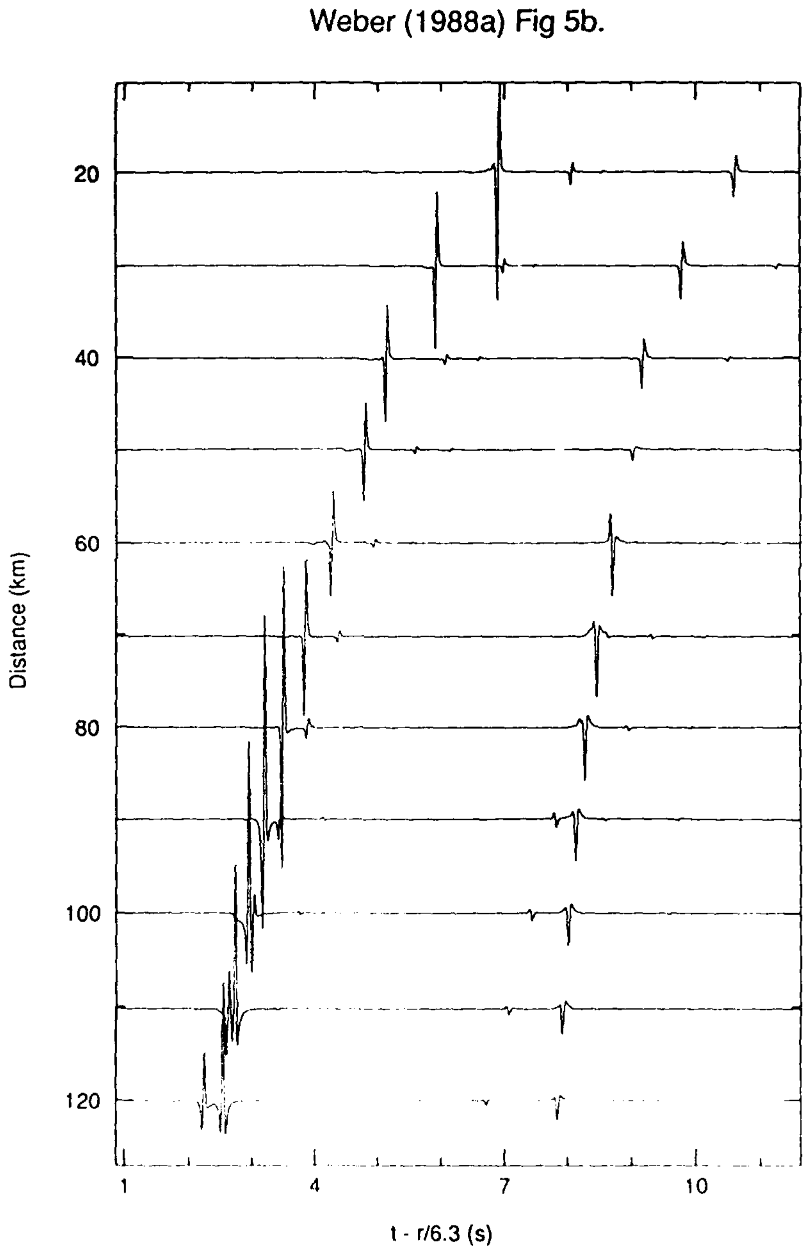

Figure 5. Gaussian beam synthetic seismograms for an explosive source in a two-layer crust plotted with a reducing velocity of 6.3 km/s. Phases include reflections off the crustal interfaces as well as converted phases but not the direct *P* wave.

The model used for the second test, that of a syncline approximated by 28 linear segments, was shown as W88a-Figure 9 and here as Figure 6. One third of the 300 SH beams emanating from a line source at x=0.4 km and reflecting off the syncline are plotted. Weber drew comparisons between a finite difference calculation for the syncline and three Gaussian beam options in W88a-Figure 10. These same three options are shown here in Figure 7. Of the three, only that for option 6 (Figure 7c) differs appreciably from that shown in W88a-Figure 10.

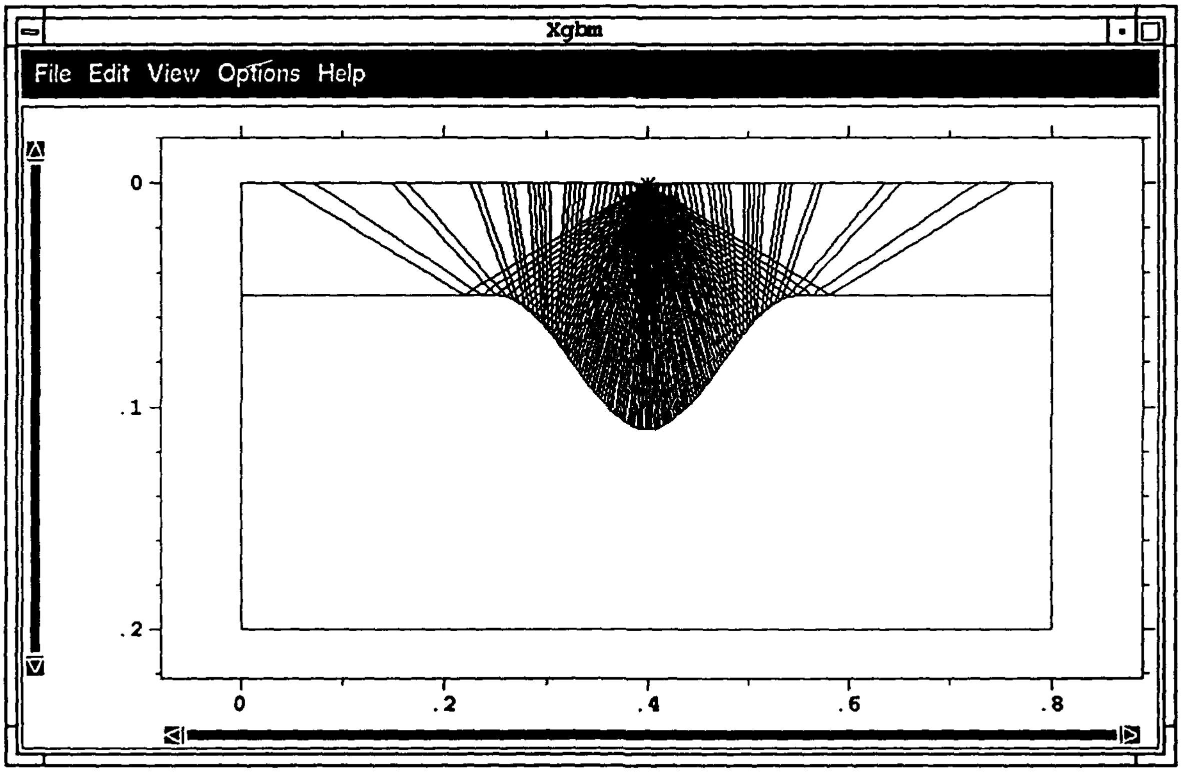

Figure 6. Syncline test model with 100 *SH* beams traced from a source positioned at (0.4, 0.0). The crust parameters are ρ=2.0 g/cm^3, v_s=1.5 km/s; that of the half-space, ρ=1.0 g/cm^3, vs=1.0 km/s. The syncline itself is a sinusoid approximated by 28 linear segments.

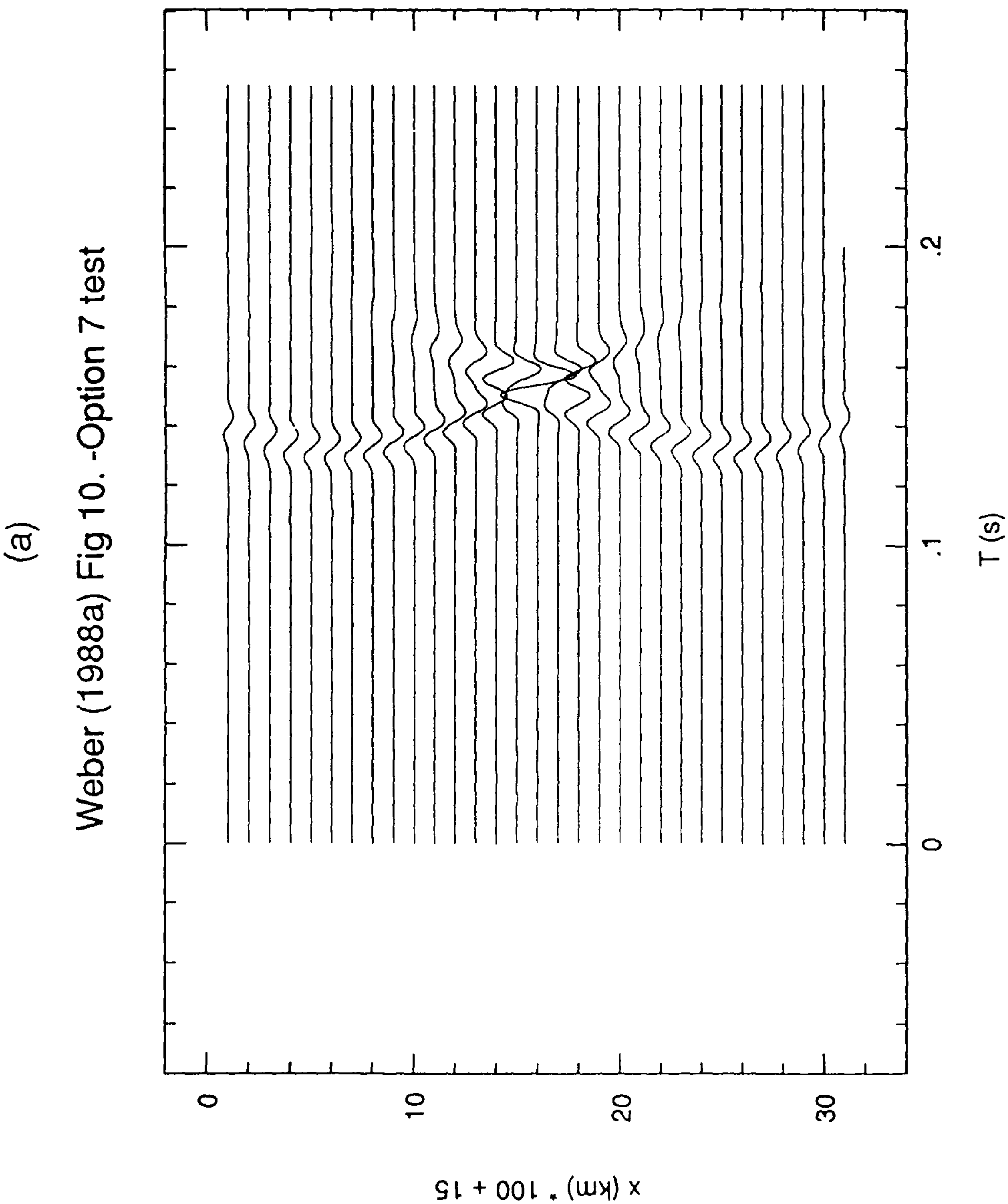

Figure 7a. Gaussian beam synthetic seismograms computed for syncline model of Fig. 6 and receivers positioned from x = [-15.0,15.0] at 1 km increments. Beam option #7 was used here. This should be compared to W88a-Figure 10b.

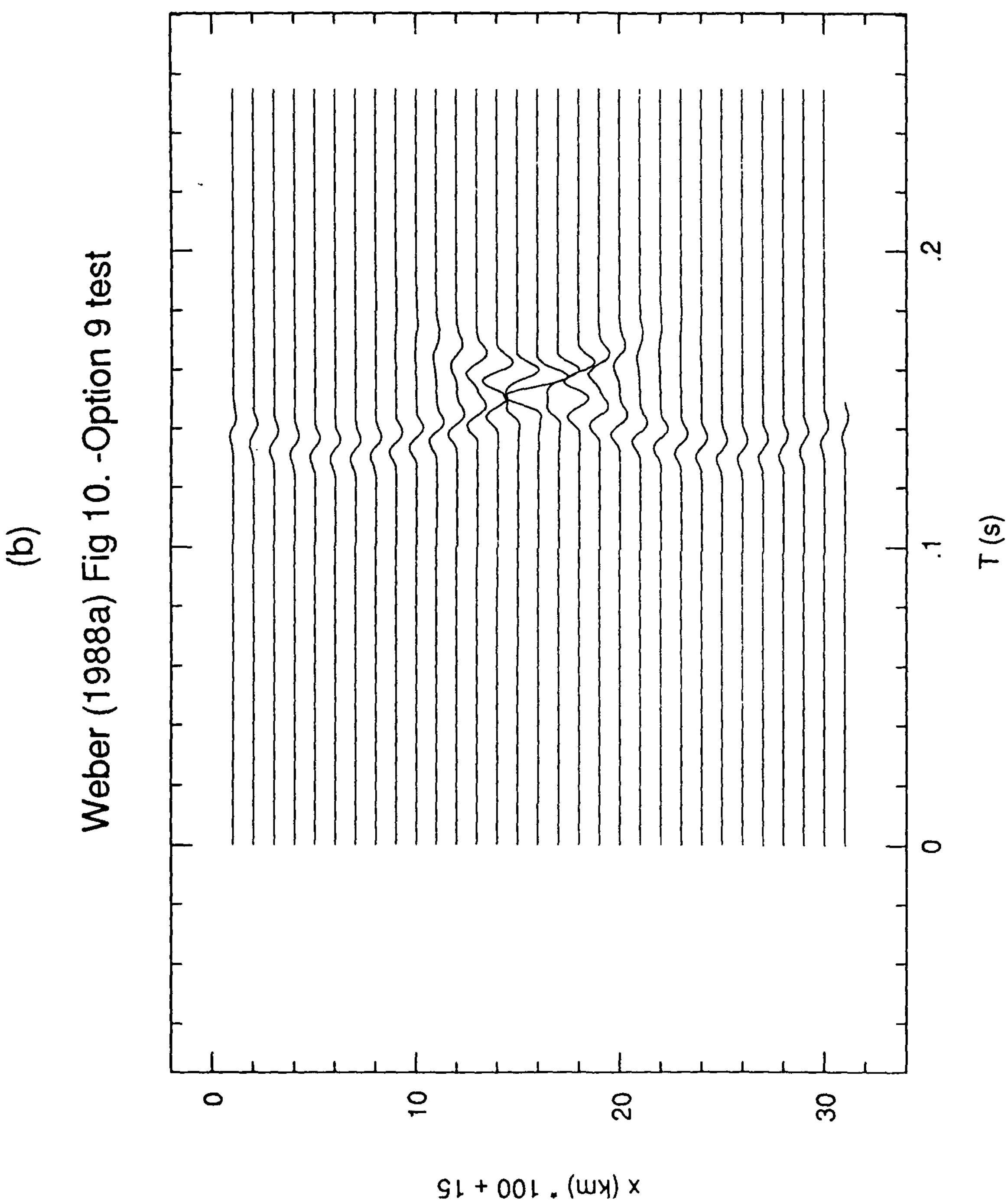

Figure 7b. Gaussian beam synthetic seismograms as in Fig. 7a but for beam option #9. This should be compared to W88a-Figure 10c.

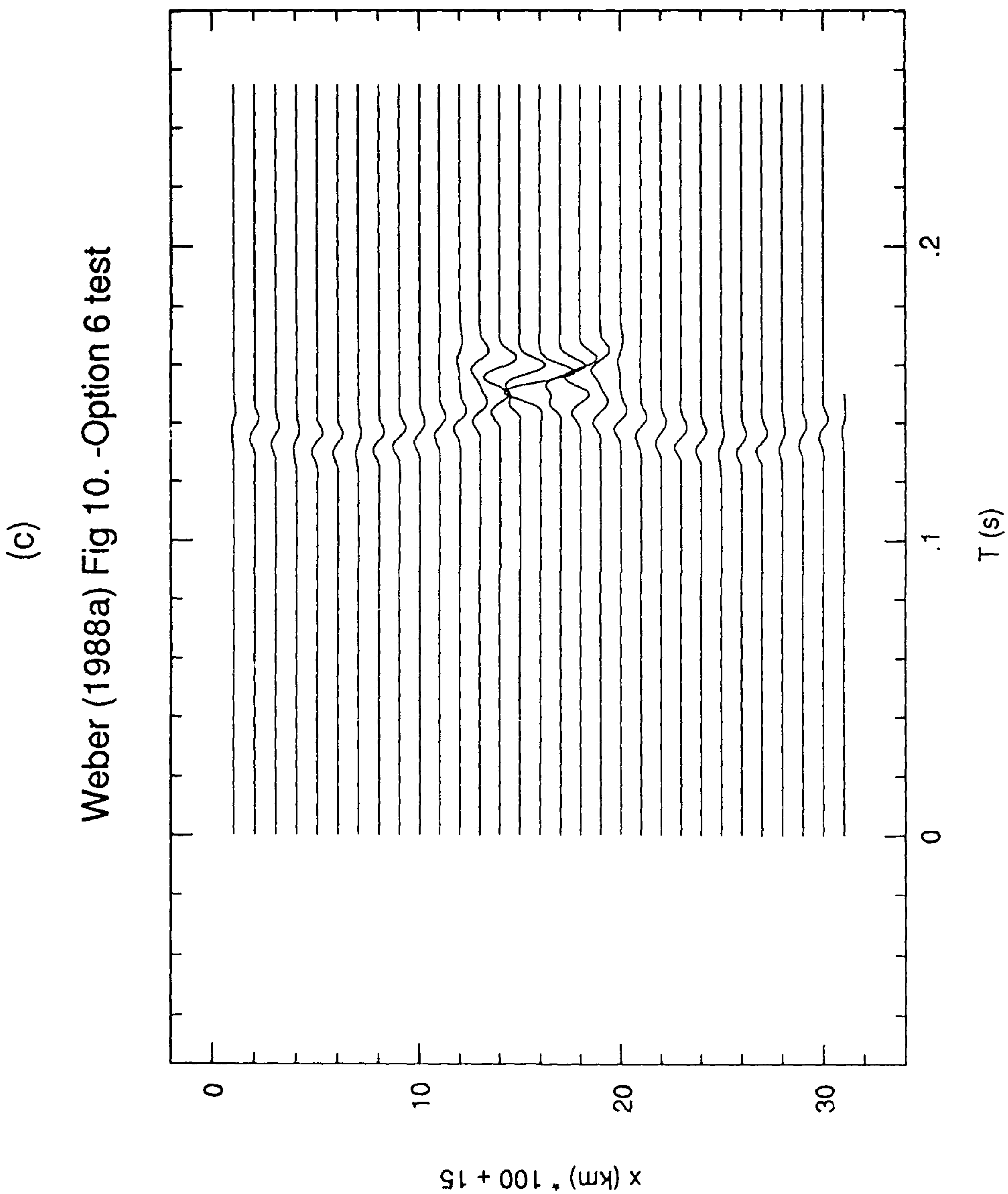

Figure 7c. Gaussian beam synthetic seismograms as in Fig. 7a but for beam option #6. This should be compared to W88a-Figure 10d.

The third and final model tested was that of a low-velocity lens, as in W88a-Figure 11. *SH* rays traced through the model are shown in Figure 8. A line source is placed at a depth of 100 km directly beneath the lens whose dimensions are 30 km in breadth and which extends from 15-50 km in depth. The velocity at the center of the lens is 5.75 km/s, and increases linearly outward until it matches the 8.0 km/s of the half-space.

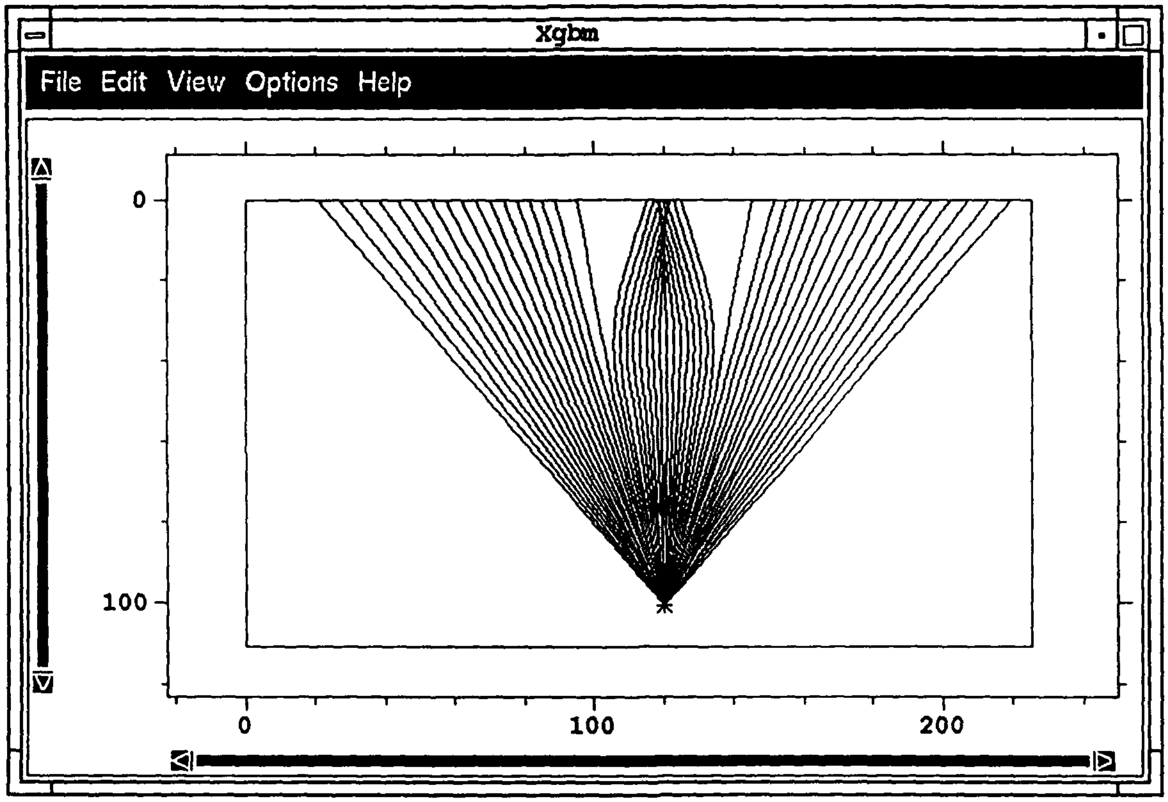

Figure 8. Low velocity (v_s=5.75km/s) lens embedded in a faster (v_s=8.0km/s) half-space. *SH* beams are traced from a source positioned at (120.0, 100) km. Corresponding seismograms are shown in Figure 9.

The transverse traces computed for this model are shown in Figure 9 and should be compared to W88a-Figure 12. With the possible exception of the trace for x=5 km, there is excellent agreement. That single trace matches fairly well and might compare even better if the attenuation parameters of Weber's model were known.

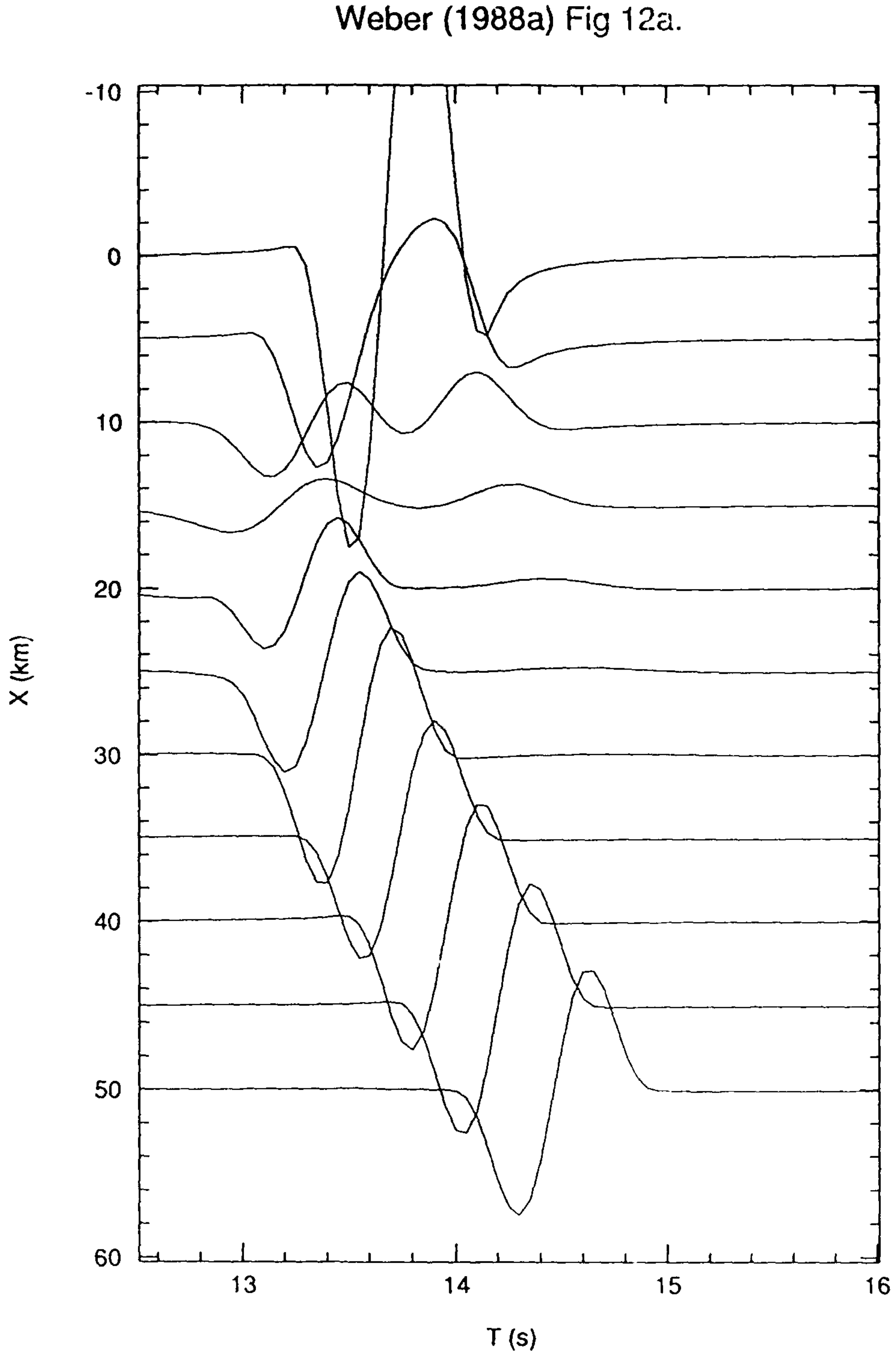

Figure 9. Gaussian beam transverse synthetic seismograms for the low velocity lens model of Fig. 8 for receivers at x = [0, 60] km at 5 km intervals. These results should be compared to W88a-Figure 12.

7. CONCLUSIONS

The package of programs described in this report offers the DARPA seismological research community a useful tool to investigate the effect of lateral structure on seismic waveforms. The graphics package for manipulating models is straightforward to apply and has been carefully tailored to integrate with other programs available at CSS. A User's Manual is available in Postscript format which may be downloaded along with the software package itself by anonymous ftp from CSS. This manual includes extensive tutorials to aid first-time users with the programs' operation as well as installation notes for the package. Comments on any aspect of the package may be directed to the Principal Investigators, davis@seismo.css.gov and ihenson@seismo.css.gov.

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